Dilution of Wastewater Discharges from Moving Cruise Ships

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***Abstract* - The U.S. Environmental Protection Agency (EPA) conducted a survey using EPA's *Ocean Survey Vessel Peter W. Anderson* to track and quantify the dilution and dispersal of wastewater discharges behind four large cruise ships. Wastewater holding tanks were spiked with rhodamine dye before discharge. During the discharge of the wastewater, drogued buoys were released at two minutes intervals to permit visual tracking of the plume. A tow fish with a fluorometer was towed through the plume to measure the dimensions of the plume and dye concentration. Dilution of the discharge was calculated based on the concentration of dye in the plume and the initial concentration of the dye in the wastewater holding tanks. Results indicate that discharges behind cruise ships moving at between 9 and 17 knots are rapidly diluted by a factor of 260,000:1 to 580,000:1. These results are larger than dilution factors estimated by previous modeling efforts. This suggests that previous studies underestimate the impact of turbulence caused by the propellers and displacement of the ship's hull.**

I. INTRODUCTION

With the growth in the size and popularity of cruising, concerns about the impacts of this industry on the marine environment have increased. Cruise ships are capable of carrying thousands of passengers and producing hundreds of thousands of gallons of wastewater daily. The impacts of the discharge of this wastewater on the environment are poorly understood. Accurately determining the impacts of discharges from cruise ships will require information on the quality and volume of the wastewater, the characteristics of the receiving environment, and the short and long-term fate of the wastewater and constituents. This study attempts to quantify the dilution of discharges from moving cruise ships within a few minutes to a few hours after discharge.

Previous studies of dilution of wastewater discharges behind cruise ships are based on modeling efforts rather than field observations. Colonell et al. [1] considered dilution in the minutes (near-field dilution) after discharge occurs and over longer time scales (far-field dilution). To model near-field dilution, two factors were considered. First, the mixing associated with the injection of the jet of wastewater into the surrounding water as the ship travels, and second the mixing caused by the turbulent boundary layer associated with the movement of the ship's hull. Based on this approach, Colonell et al. estimate that effluent discharged at a rate of 200 meters^3 second^{-1} from a cruise ship traveling at between 6 and 10 knots would be diluted by a factor of between 600 and 2,500 within minutes of discharge [1]. This modeling effort also concluded that the plume of wastewater is not likely to be impacted by the turbulence caused by the propellers [1]. In addition, the model does not account for turbulence associated with the displacement of the ship's hull.

Kim took a simpler approach to modeling dilution behind a moving vessel [2]. Based on the assumption that wastewater would be homogeneously mixed into an area 20 meters deep by 60 meters wide along the ship's path, Kim calculated that the dilution factor for discharges from a vessel ranges from 44,400 at 4 knots to 110,000 at 10 knots [2]. However, this study did not attempt to characterize the amount of time that would elapse before this level of dilution was achieved.

The Alaska Cruise Ship Initiative Science Panel has also made estimates of the dilution of wastewater behind cruise ships as part of their efforts to evaluate the environmental impacts of cruise ships. They developed a model that estimates the minimum dilution factor behind moving cruise ships with the following equation:

$$\text{Dilution factor} = (\text{ship width} \times \text{ship draft} \times \text{ship speed})/(\text{discharge rate}). \qquad (1.1)$$

Where ship width and draft are in meters, ship speed is in meters second^{-1}, and the discharge rate is in meters^3 second^{-1} [3]. Using (1.1), the Science Panel estimates the dilution factor of between 10,500 at 6 knots and 39,600 at 18 knots. The Science Panel has subsequently modified this formula in light of previously published data from this study [4], [5].

In contrast to the efforts previously discussed, the study presented here measured the dilution of discharges behind

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cruise ships in the field. To quantify dilution, we spiked wastewater tanks with rhodamine dye. The crew of the cruise ship then emptied the tanks while the vessel was underway and we monitored the resulting plume of dye using a towed instrument package containing a flourometer.

Results indicate that, on average, wastewater is diluted by a factor of between 260,000 and 580,000 within 10 minutes of discharge. These results are much greater than those predicted by the modeling efforts described above [1], [2], [3]. The contrasts between our results and previous modeling efforts suggest that previous efforts underestimated the extent to which turbulence imparted by the ship's hull and propellers act to dilute discharges from moving vessels.

II. METHODS

A. Study Conditions

EPA coordinated with the International Council of Cruise Lines, Royal Caribbean Cruise Lines, and Carnival Cruise Lines to perform this survey. We tracked discharges from four cruise ships (Table 1), traveling at between 9 and 19 knots.

TABLE 1
VESSEL SPECIFICATIONS

	Majesty	Explorer	Paradise	Fascination
Length (m)	268.3	311.13	260.6	260.6
Beam (m)	32.6	38.6	31.4	31.4
Draught (m)	7.7	8.8	7.75	7.75
Wastewater tank volume (L)	113,000	16,700	108,000	27,000
Depth of discharge port (m)	5.6	6.4	6	6.35
Passenger capacity	2,354	3,114	2.634	2.634

Discharges from the vessels were tracked while the vessels were just over 12 miles offshore of Miami, Florida. Water depths in the study area ranged from 90 to 300 meters. Conditions during the survey were calm. Data from an acoustic Doppler current profiler (ADCP) onboard the Royal Caribbean Cruise Line's *Explorer* indicate that the currents in the upper water column were consistent; no shear was evident.

B. Dye Addition and Detection

We added between 22 and 27 kilograms of rhodamine dye dissolved in between 114 and 137 liters of water to empty wastewater holding tanks aboard each cruise ship. Following the addition of dye, the crew of the cruise ship filled the tanks with wastewater. Discharge occurred five to nine hours after dye addition to the tanks.

The cruise ship crew took five samples from the wastewater tank prior to discharge. These samples were stored at 5°C until analysis. We tested the samples for flouresence to determine the concentration of dye in the holding tank prior to discharge. Initial concentrations in the tanks were also calculated based on the volume of the wastewater in the tank and the amount of dye added.

C. Plume Tracking

During the release of the dye from each cruise ship, drogued buoys equipped with lights and radar reflectors were released at approximately two-minute intervals (beginning when dye release was initiated) to permit visual tracking of the sub-surface plume. The drogues for each buoy were tethered ~2 meters below the surface.

After the cruise ship deployed the first buoy at the beginning of the dye release, the *OSVAnderson*, while towing an instrument package described below, maneuvered to enter the plume on a track nearly perpendicular to the cruise ship's heading. The instrument package was towed approximately 2 meters below the surface for the first transect through the plume. The initial transect occurred within a few minutes of the cruise ship passing through that area. Subsequent transects through the plume were conducted following a serpentine pattern (Fig. 1). The second, third, and fourth transects were, with a few exceptions, taken at approximately 5, 8, and 12 meters depth, respectively. The *OSV Anderson* made between 7 and 23 passes through the dye plume from each ship.

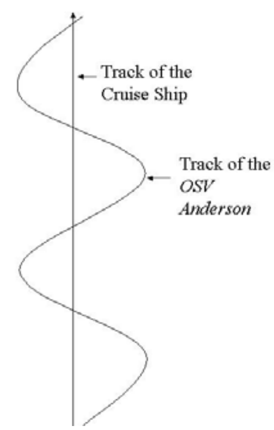

Fig. 1. Track lines of survey vessels and cruise ship.

A towfish with sensor package was used to conduct plume-tracking activities. We deployed the instrument package approximately 10 feet off of the port side of the *OSV Anderson* to minimize the impact of the wake and propellers on the monitoring activities. The sensor package included conductivity, temperature, depth (CTD) sensor, and a fluorometer. *In-situ* fluorescence measurements were recorded continuously. We corrected all rhodamine dye fluorescence data for temperature.

To calibrate the flourometer, we took between two and nine discrete samples from each plume and stored them at 5°C until analysis.

D. Calculations

We calculated average dye concentrations along each transect for each cruise ship from the point where dye values exceeded background levels until they returned to

background levels. We estimated the plume width as the area above background dye concentration.

We calculated dilution factors two ways. One based on the concentration of dye in the tank and the plume (referred to as measured dilution). The other based on the dimension of the plume and mass balance considerations (referred to as calculated dilution). Measured dilution was calculated using the concentration of dye in the wastewater tank (calculated based on the volume of the tank and the amount of dye added) and the average concentration of dye measured in either the first or second pass through the plume. We used the second pass if the average concentration measured was higher than the first pass; because we believe, in those circumstances, the main body of the plume was below the depth of the first pass (which was at 2 meters depth). The second pass was completed within approximately 5 minutes of the cruise ship passing the *OSV Anderson*.

Calculated dilution was determined with the following equation based on mass balance considerations:

$$F=(H\%W\%V)/D. \quad (2.1)$$

Where F is the estimated dilution factor, H is the estimated depth of the plume, W is the width of the plume, V is the velocity of the vessel, and D is the rate of wastewater discharge.

III. RESULTS AND DISCUSSION

Based on the amount of dye added to the tank, we calculated the concentrations of dye in the tanks of the various cruise ships to be between 0.42 and 5.5 grams liter^{-1} (Table 2). Dye concentrations measured with the flourometer on discrete samples from the wastewater tanks were variable (Table 2). We believe this variability was caused either by errors in diluting the samples before measuring the fluorescence or incomplete mixing of the dye in the tank before sampling. We used the calculated dye concentrations for estimating the dilution factors, recognizing that this approach may underestimate uncertainty associated with incomplete mixing of the dye in the wastewater tanks.

TABLE 2
DYE CONCENTRATIONS IN TANK (all units in g L^{-1})

	Majesty	Explorer	Paradise	Fascination
Calculated Concentration	0.200	1.44	0.244	1.00
Average Measured (StDev)	0.11 (0.06)	1.0 (0.5)	0.3 (0.1)	1.0 (0.8)
Replicate 1	0.12	1.08	0.17	0.98
Replicate 2	0.14	0.84	0.18	0.62
Replicate 3	0.17	0.86	0.34	0.52
Replicate 4	0.00	0.47	0.43	0.40
Replicate 5	0.10	1.77	0.23	2.39

The initial width of the plumes ranged from 66-182 meters (Table 3). As the surveys progressed, the width of the plume varied, but tended to increase. The plumes of all four cruise-ship exhibited significant dye concentrations in the surface waters. However, for the *Majesty* and *Paradise*, the dye plumes were most concentrated between 5 and 10 meters in depth and both plumes penetrated the water column to a depth of approximately 18 meters. The dye plume of the *Explorer* was relatively concentrated at the surface and penetrated no deeper than 10 to 12 meters.

TABLE 3
PLUME CHARACTERISTICS AND DILUTION FACTORS

	Majesty	Explorer	Paradise	Fascination
Vessel Speed (knots)	17.4	19	15	9.1
Discharge Rate ($m^3 h^{-1}$)	112	56	136	72
Tank Concentration (g L^{-1})	0.200	1.44	0.244	1.00
Average[1] Concentration in Plume (g L^{-1})	4.2 E -7	5. 1E -6	4.2 E -7	3.8 E -6
Maximum Concentration in Plume (g L^{-1})	1.22 E -6	3.62 E -5	1.3 E -6	9.4 E -6
Width of Plume (m)	66	147	182	88
Depth of Plume (m)	18	10	18	12.5
Measured Initial Dilution	480,000	280,000	580,000	260,000
Calculated Dilution Factor	340,000	900,000	660,000	260,000
Minimum Dilution	160,000	40,000	190,000	110,000

[1]Average concentration of the transect with the highest average.

Initial measured dilution factors were estimated to be between 260,000 and 580,000 within a few minutes following discharge (Table 3). These values are in reasonable agreement with the dilution factors estimated with (2.1) for all vessels except the *Explorer* (Table 3). Minimum dilution factors (based on the maximum concentrations observed in the plume) ranged between 40,000 and 190,000 (Table 3). This finding indicates that there are portions of the plume where wastewater concentration can be two or more times higher than the average in the plume.

Results from the very similar Carnival Cruise Line ships, the *Fascination* and *Paradise*, illustrate the impact of speed on dilution. The dilution factor measured behind the *Paradise*, traveling at 15 knots, was slightly more than twice the dilution factor behind the *Fascination*, traveling at 9 knots. This contrast was evident despite the fact that the Paradise was discharging at nearly twice the rate of the *Fascination* (Table 3).

However, data from the Majesty and Explorer suggest that vessel design and configuration may also have a significant impact on dilution factors. Although the *Majesty* and *Explorer* were both traveling at similar rates (17.4 and 19.0

knots respectively), the dilution factor for the *Majesty* is nearly 2 times that for the *Explorer* (Table 3).

There is a large discrepancy between the measured results and the calculated results for the *Explorer*(Table 3). One possible explanation for this discrepancy is that incomplete mixing of the dye in the wastewater tank resulted in higher than expected dye concentrations in the initial wastewater stream [1].

After the initial dilution, the plumes continued to slowly disperse. As the survey progressed, the average dilution factor calculated for each pass tended to increase (Fig. 2). With a few exceptions, dilution factors increased approximately one order of magnitude within 3 to 4 hours. At the end of each sampling period the drogues deployed during the discharge of dye were still in straight lines and the plumes were intact, but wide and dilute.

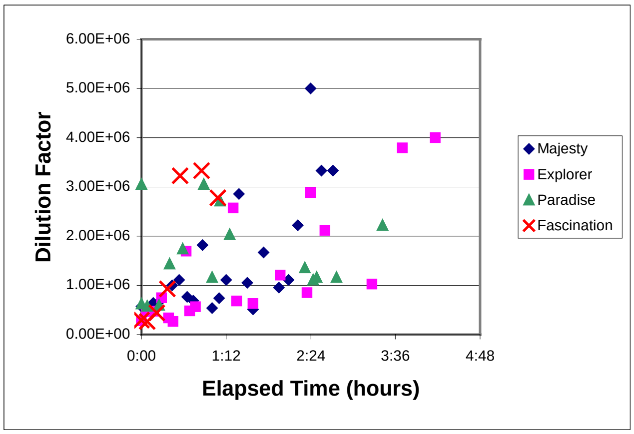

Fig. 2. Measured dilution of the plumes during the course of the surveys. Note: Figure does not include two high dilution factors for the *Paradise* of 1.2 E 7 and 2.4 E 7 at times 1:25 and 1:57 respectively.

IV. CONCLUSIONS

Results indicate that wastewater discharged from moving cruise ships is diluted, on average, by a factor of between 260,000 and 580,000 within 10 minutes of discharge. This value is higher than any previously published estimate of dilution behind moving cruise ships we are aware of. This discrepancy suggests that previous studies have underestimated the impacts of the turbulence caused by the propellers and the displacement of the vessels hull. This study also indicates that ship speed has a large impact on the magnitude of effluent dilution. Other factors likely to affect dilution include discharge rate, and hull characteristics

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